Geographical and stratigraphical provenance changes in the Lower Cretaceous McMurray Formation, Alberta, Canada, as revealed by heavy mineral analysis and detrital zircon U-Pb geochronology

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Summary

Interpretations of detrital zircon U-Pb geochronology data and results of heavy mineral (HM) analysis conducted on samples from the Lower Cretaceous McMurray Formation of the Athabasca Oil Sands (north-eastern Alberta, Canada - see Figure 1a) resulted in the recognition of geographical and stratigraphical changes in the provenance of the McMurray Fm., the latter being related to changes in the size of the fluvial channels that deposited the analysed successions. These interpretations also ultimately lead to the identification of the entry points – into the main channel – of fluvial tributaries that drained different geological terranes. These information are fundamental to reconstruct the reservoir geology, in particular when a detailed model is required for production optimisation.

Introduction

Having a detailed geological model for a reservoir in place, which would highlight spatial changes in lithology, is of vital importance to optimise hydrocarbon production. Such a situation is particularly relevant to reservoirs containing bitumen, as Steam Assisted Gravity Drainage (SAGD) recovery method needs to be applied and it is sensitive to lithological heterogeneity (e.g., Strobl *et al.* 1997). The SAGD method commonly has been applied to the Athabasca Oil Sands and, in particular, to the McMurray Formation.

The McMurray Fm. mostly consists of fluvial deposits (point bar and abandoned channel deposits) that migrated laterally and downstream, resulting in a complex sedimentary architecture. The point bar deposits, which are the major targets for exploration, are characterised by sandstones and siltstones with inclined heterolithic stratification (IHS) and silty drapes at their tops, with reservoir quality being governed by the thickness and distribution of the IHS siltstones (Strobl *et al.* 1997; Wightman & Pemberton 1997; Labreque *et al.* 2011). Mud-clast rich breccias form part of the channel deposits (Mossop & Flach 1983; Hubbard *et al.* 2011). The lower McMurray Fm. was deposited by a fluvial system characterised by relatively small fluvial channels and drained a relatively restricted area (Benyon *et al.* 2016 and references therein), whilst the middle-upper formation is considered to be associated with a fluvial system which drained an area extended as far away as the Appalachian and Grenvillian provinces (Turner & Peterson 2004; Roca & Nadon 2007; Dickinson & Gehrels 2008; Blum & Pecha 2014).

In fluvial successions paleodrainage reconstructions – which are constrained by sediment provenance interpretations – generate useful information to produce a detailed geological model for the reservoir. In provenance studies, the best results are obtained by adopting a multi-disciplinary approach involving several techniques, including heavy mineral analysis and U-Pb geochronology (e.g., Lihou & Mange-Rajetzky 1996; Eynatten & Gaupp 1999; Morton *et al.* 2005). Each of these analyses has been undertaken on the McMurray Fm. (e.g., Mellon, 1956; Benyon *et al.,* 2016): the purpose of the current study is to demonstrate the importance of employing both techniques in combination to clarify the complex provenance of the McMurray Formation.

Theory and Method

Heavy minerals are those minerals having density above 2.9 g/cm^3. They usually constitute less than 1% of a clastic rock, but are especially important with respect to provenance studies, as many (e.g., kyanite, sillimanite and spinel) originate from relatively specific 'parent' rocks. However, when employing HM analysis as part of a provenance study, taking into account the processes capable of modifying the HM assemblages is needed. Such processes include hydraulic sorting and mineral alteration (Morton & Hallsworth 1999). Hydraulic sorting exerts a considerable influence on fluvial deposits and is related to the size, density and shape of grains: the process can bring concentrations of ultradense HM (those with density > 3.8 g/cm^3, e.g., zircon, rutile and opaque grains) in very fine grained sans and accumulations of less dense HM (those with densities between 2.9 and 3.8 g/cm^3, e.g., apatite and kyanite) in fine grained sands (e.g., Garzanti *et al.* 2008, 2010). The alteration of minerals, via weathering and dissolution, is controlled by the chemical stability of each mineral and favours the preservation of minerals such as zircon, tourmaline, and rutile which are among the most stable HM.

Heavy minerals can be concentrated and separated from disaggregated sedimentary rocks by using 'heavy' liquids (e.g., a lithium metatungstate solution having a density of 2.89 g/cm^3). Subsequently, the separated HM grains can be identified via either optical analysis or Raman spectroscopy. Details about the separation of HM grains and their optical identification are given in Mange & Maurer (1992), whereas their identification by Raman spectroscopy is described in Andò & Garzanti (2013).

Additional techniques, including Frantz magnetic separation, are employed to isolate detrital zircon grains, with their ages being determined by U-Pb geochronology (via laser ablation - inductively-coupled plasma - mass spectrometry (LA-ICP-MS) analysis). To take account of instrument bias, the results of the analysis are compared with the Plesovice zircon standard (Sláma *et al.* 2008). The ages of the zircon grains are presented in the form of concordia diagrams (Ludwig 2008) and any particularly discordant data are rejected. The zircon age data obtained by ourselves are summarised here, along with published data from Benyon *et al.* (2014) and (2016).

Case Study

The most frequently observed heavy mineral assemblages in the McMurray Formation comprise the ultrastable zircon, tourmaline and rutile, which together make up around 50% to 75% of most assemblages, and HM derived from high-grade metamorphic rocks, e.g., garnet, kyanite and staurolite, along with anatase, apatite, chloritoid, monazite and titanite, and other scarcer species. Geographical changes in the proportions of the above HM have been recognised in the formation across north-eastern Alberta - for example, the combined abundance of ultrastable minerals decreases from south to north, whereas the combined abundance of the HM derived from high-grade metamorphic rocks increases in the same direction. Furthermore, the McMurray Fm. in the southernmost part of the study area is characterised by HM assemblages in which chloritoid and anatase are relatively frequent, whereas garnet is common in the northernmost part of the study area (Figure 1b). Zircon grains of Grenvillian (c.900Ma to 1300Ma) and Appalachian (c.300Ma to 700Ma) age are predominant in the southern part of the study area. Older zircon grains (c.1800Ma to 2000Ma, with a peak at c.1800Ma to 1900Ma) are also observed and are associated with Grenvillian-aged grains and/or grains derived from the Canadian Shield (grains older than c.2500 Ma). Furthermore, some zircon grains of Cordilleran age (younger than c.250Ma) have been recorded (Figure 1a and 1b). Stratigraphical changes are also observed, for example chloritoid abundance increases over the formation in the northernmost part of the study area. In the central part (marked by a red dot on Figure 1b) kyanite and staurolite abundances decrease up-sequence and zircon grains of c.1800Ma to 1900Ma and of > 2500Ma ages are abundant at the base of the study interval, whereas zircon grains of Grenvillian age are found in large proportions in the shallower sediments (Figure 1c).

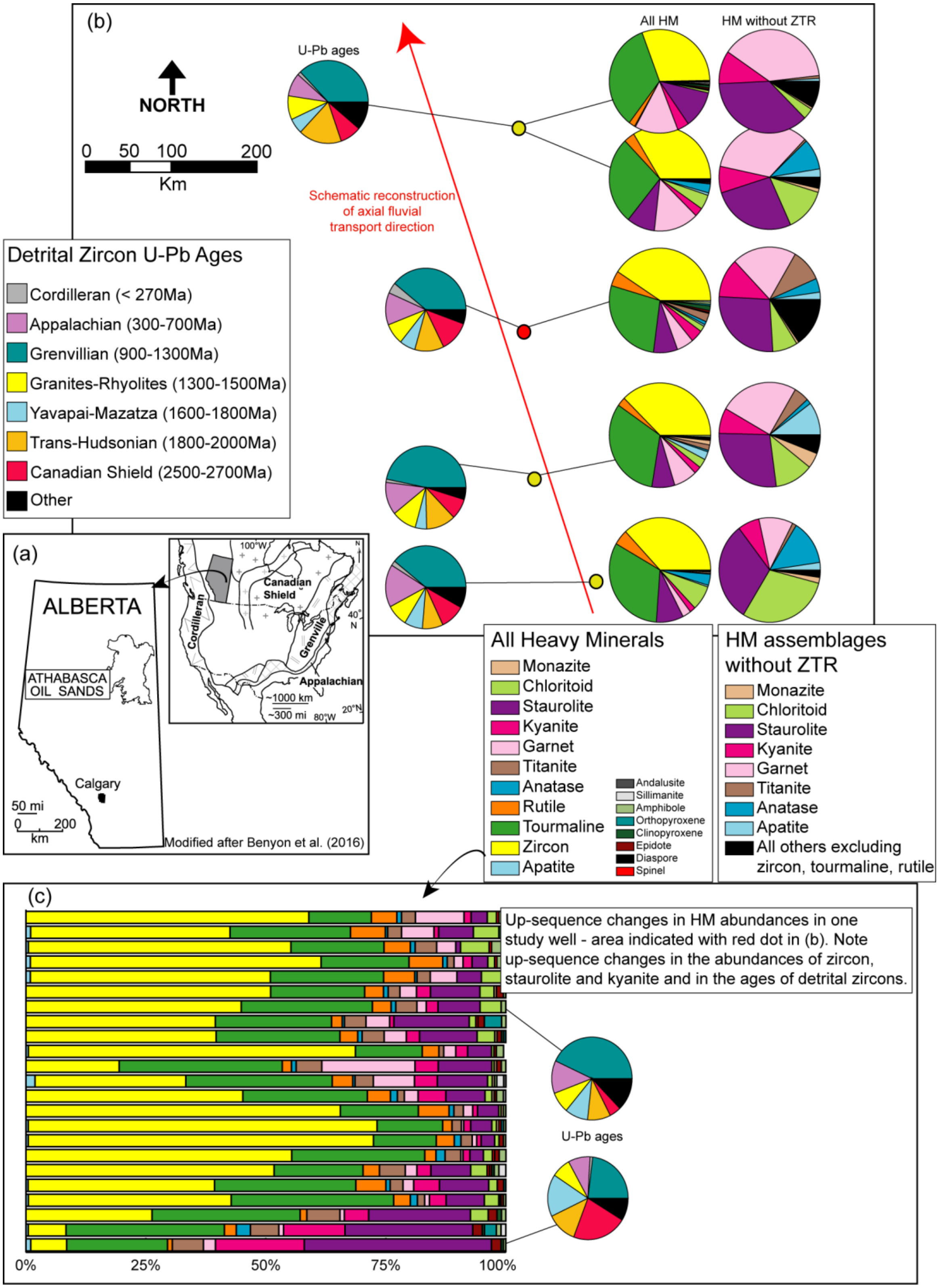

Figure 1. Location of the Athabasca Oil Sands (a); changes in HM assemblages and detrital zircon U-Pb age populations occurring in the McMurray Formation from south to north (b) and up-sequence (c). Figure 1b - pie-charts show average of data in each part of the study area; ZTR: sum of zircon, tourmaline and rutile abundances. Figure 1c - each pie-chart represents one sample.

Within this study area observed HM assemblages could be interpreted as the effect of hydraulic sorting. For example, kyanite has been predominantly found within the coarse grained sandstones, where it occurs as relatively large grains. Moreover, statistical analysis of the dataset shows tourmaline is not associated with the other ultrastable HM (zircon and rutile), which are denser than tourmaline and are generally concentrated in finer grain size sediments than those containing abundant tourmaline. Nevertheless, the HM assemblages and the zircon age populations show similar stratigraphical variations, which suggests these variations reflect provenance changes, particularly when considering kyanite, staurolite and the zircon grains aged c.1800Ma to 1900Ma presumably have originated from the same source areas. The presence of kyanite and staurolite has been recorded in the Athabasca granulite terrane, in the Canadian Shield in northern Saskatchewan and in the gneisses and schists of British Columbia (Hancock & Simandl 1995; Snoeynbos *et al.* 1995; Regan *et al.* 2014), and zircon grains aged between c.1800Ma and 1900Ma are believed to have been derived originally from the Trans-Hudson province of the Canadian Shield, and have been recycled from the clastic rocks of the Athabasca Group of Alberta and Saskatchewan and of the western North America Cordillera (Raines *et al.* 2013; Gehrels & Pecha 2014).

Possible source areas for kyanite and staurolite and c.1800Ma to 1900Ma aged zircon grains are much closer to the McMurray Formation than the Appalachian and Grenvillian provinces. If so, then the postulated stratigraphical changes in the provenance of the formation could be related to changes in the size of river channels and in the size of the fluvial drainage area. The lower McMurray Fm. could contain detrital material originating from areas to the east, e.g., the Trans-Hudson province, and / or to the west, e.g., the western North America Cordillera, of the depositional area. During the deposition of middle and upper McMurray Fm., additional abundant sediment derived from other areas located as far away as the Grenvillian province was being brought in. Moreover, the geographical changes in the HM assemblages and the zircon age populations described above probably reflect the location of fluvial tributaries that drained areas characterised by different lithologies.

Raman HM analysis performed in the northernmost study area shows large abundance of Type A garnet grains (i.e., almandine + spessartine + pyrope garnet; Mange & Morton, 2007), suggesting provenance of garnet from granulite-facies metamorphic rocks, which for example occur in Athabasca (Mahan *et al.* 2008, Regan *et al.* 2014). These data help in further constraining the provenance of the McMurray Fm. and refining the drainage models.

Conclusions

Interpretations of heavy mineral assemblages and detrital zircon U-Pb age populations give important information on the sediment provenance of the McMurray Formation. Contribution of lateral tributaries to the sedimentary budget is evident in the lower McMurray Fm., whereas the middle-upper formation contains detrital material derived by areas located as far away as the Grenvillian province. Accurate mapping of the data reveals where the entry points of lateral tributaries were located. Results can be employed to model the reservoir geology of the McMurray Formation, which has complicated geometries due to deposition by channels that migrated laterally and downstream. Knowledge of the reservoir geology will help to enhance bitumen recovery via the Steam Assisted Gravity Drainage method.

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